7 Calibrations in Process Control

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INTRODUCTION

In process industries, a critical part of asset management strategy of a company is the calibration of the process instruments and other devices. Often companies invest millions of dollars on instruments and they find that uncalibrated instruments provide misinformation that can cost extra millions of dollars. Also, instruments drift from calibrated status under operational conditions resulting in misleading readings. Process plants such as pharmaceuticals, chemicals, nuclear, metal processing, paper, food and beverage, power, oil and gas industries need to make sure that their instrumentation in the plant such as temperature sensors, pressure transducers, flow meters, and the like are performing as expected and measuring within the specified tolerances. If the representations of process variables drift away from their specification range, it can result in costly production downtime, create adverse safety issues, and lead to the production of inferior quality goods.

The ability of an instrument or a device to accurately measure the changes in a physical quantity depends on a number of factors, such as the time in service, temperature, vibrations, humidity, environmental exposure, corrosion, electronic malfunctioning, drift, changes in application conditions, and so on. Calibration quantifies the change in the measurements and hence the adjustments on the device become necessary to decrease or completely eliminate possible errors. Hence, calibration of devices ensures that the processes are well controlled and the products meet expected specifications. The results can be used in process optimization, asset control, and the safety of plants leading to a better management of the plant performance.

Definitions

The Oxford English Dictionary defines the term "calibrate" as "(1) mark (a gauge or instrument) with a standard scale of readings, (2) compare the readings of (an instrument) with those of a standard, and (3) adjust (experimental results) to take external factors into account or to allow comparison with other data."

Some of the following terms that will often be used in this chapter are:

Calibration procedure: A documented, verified, and validated process that describes a set of operations in accordance to a given method

Calibration provider: Laboratory or facility including personnel that performs calibration in an established location

Errors: Result of a measurement minus the true value of the measurand

Reference standard: Measurement standard having the highest metrological quality available in an organization

ERRORS AND UNCERTAINTIES IN CALIBRATIONS

Calibration refers to the act of evaluating and adjusting the precision and accuracy of measurement equipment. Before the calibration is attempted, the equipment used in the process for calibrations must be calibrated to ensure that they themselves are performing error free. Although this calibration and accuracy of measurement instruments are usually performed by the equipment manufacturers, it may also be necessary for the operators to perform a "user calibration" of the equipment. The user calibration includes the equipment settings, test setup, and verification of correct application to validate that the desired levels of precision and accuracy are achieved. The term *calibration standard* is used when an absolute measured value and the reference standards are traceable back to national and international primary standards.

Despite strict rules and procedures most calibrations are likely to have errors and uncertainties in the calibrated values. These calibration errors and uncertainties can be evaluated by implementing Type A and/or Type B evaluations techniques.

1. *Type A* evaluation applies to errors, uncertainties, and bias by using statistical techniques. The ISO guidelines, such as ISO 11095, give guidance on how to assess, correct, and calculate errors, uncertainties, and biases.
2. *Type B* evaluations can apply to errors, uncertainties and bias too but the calculation of the uncertainty component is not based on a statistical analysis but they are based on factors such as experience, scientific judgment, scant data, and the use of different laboratory assessments.

However, in many situations, it may be impossible to achieve a perfect calibration because of instrument and measurement biases and uncontrollable random errors. Mathematically,

$$\text{Ideal value} = \text{Measured value} + \text{Bias} + \text{Error}$$

Similarly, reference value may be subject to bias and error

$$\text{Ideal reference value} = \text{Reference value} + \text{Bias} + \text{Error}$$

This leads to a deficiency in the calibration as

$$\text{Deficiency} = \text{Ideal measured value} - \text{Ideal reference value}$$

Due to randomness of errors, this deficiency may not be zero, and therefore the calibration measurements may have to be repeated many times. Then, the statistical techniques can be applied to work out the calibration curves, average readings, and standard deviations. The process of collecting data for creating the calibration curve is critical to the success of the calibration program. As a rule of thumb, a minimum of 5 reference standards are required for a linear calibration curve, and 10 reference standards are sufficient for more complicated calibration models.

BENEFITS OF CALIBRATIONS

Calibration provides consistency in readings and reduces errors, thus validating the measurements universally. Usually, the calibration procedure involves comparison of the instrument against primary or secondary standards. In some cases, it may be sufficient to calibrate a device against another one with a known accuracy. After the calibration of a device or a process, future operation is considered to be error bound for a period of time under the similar operational conditions. Hence, calibration has the following benefits:

- Determines whether measurements made before the calibration were valid.
- Gives confidence on the future measurements.
- Ensures consistency and compatibility with those made elsewhere.
- Leads to repeatability and reproducibility of the processes.
- Provides confidence that products meet their specifications thus reducing legal liability. Without calibration, the product quality may be poor thus opening up legal challenges and high failure rates of the products thus increasing costs.
- Increases efficiency by ensuring that measurements are correct.
- Leads to documentation of performance of instruments and processes to meet quality standards such as those set by the ISO.
- Frequent calibrations can provide graphical view of the equipment uncertainty over time and leads to reliability in performance. This gives in service life analysis; hence depreciation and replacements can be predicted in an informed manner.
- Measurements made within international standards promotes global acceptance thus increasing competitiveness.
- Helps convenient implementation of related regulations and legislation that governs the use of equipment in a particular application.
- As the technology changes over the years, the regulations and legislation of test and measuring instruments changes continually and calibration helps compliance validity of measurements and processes under changing conditions.
- In some cases, calibration can be used as a gain; the value multiplied by some input can produced a scaled output.

An important element in calibrations is the relationship between a single measurement and the reference base for the unit of measurement as the reference base is the prime source of authority. The base units of measurement is the Le Systeme International d'Unites (SI) units maintained in the Bureau International des Poids et Mesures, Paris. These are *kilogram* for mass, *meter* for length, *second* for time, *candela* for luminous intensity, *Kelvin* for thermodynamics, *ampere* for current, and *mole* for amount of substance. Other reference bases such as *Newton* for force, *hertz* for frequency, etc. are derived from the base units and maintained by national standards institutions.

CALIBRATION METHODS AND PROCEDURES

In process control, calibration can be summarized as "a set of operations to establish a good relationship between the process variables under investigation and their representation by the measuring instruments under specified or operational conditions." A successful calibration process requires hardware and software, special equipment, and manpower.

Calibration is a process that assigns values to the response of device or an instrument relative to reference standards or to a designated process. The aim is to eliminate or reduce the errors, uncertainties, and biases in the measurements relative to the reference standard. The errors, uncertainties, and bias may be introduced by the process itself as well as by the measuring instruments. They may remain constant independent of the direction of measurement or they may change in time during the process operations.

Reference standards are used to establish a general level of consistency in measurements and to help interpret and quantify the information contained in the received signal from the field devices. Also, reference standards are useful to validate that the equipment and the process setup provide similar results from one day to the next and that similar results can be produced by different systems.

For a successful calibration, a step-by-step calibration procedure and detailed specific instructions are essential. First of all, it is necessary to prepare yourselves correctly for the calibrations. In doing so the following factors may be considered.

1. The type of calibration process to be employed
2. Calibration set up and the calibration process
3. Calibration cycles
4. Calibration records
5. Calibration reports and report keeping
6. Factors affecting calibration
7. Use of spread sheets
8. Mathematical approaches
9. In-house vs. outsourced calibration
10. Reference standards to be used
11. Hierarchy of reference standards
12. Traceability
13. ISO 9000 requirements
14. Working standards
15. Measurement uncertainties
16. Uncertainties vs. errors
17. Random and systematic errors

Once these factors have been considered an appropriate calibration procedure must be followed. Calibrations must be repeatable and mathematically expressible.

The process of calibration is carried out in a hierarchical order. At the highest level, the *primary reference standard* is assigned a value by direct comparison with the reference base of SI units. The primary standards are designated and widely acknowledged as having the highest metrological quantities that have values without reference to other standards of the same quantity. In the second level, the *secondary reference standards* are calibrated by comparing with primary standards of the same quantity by using high-precision comparisons and by making appropriate adjustments and corrections. In the third level, *working standards* are routinely used to calibrate instruments and processes against the secondary reference standards or their representatives.

Calibration Methods

There are two basic calibration methods:

1. Static calibration
2. Dynamic calibration

Static calibrations aim tuning static characteristics of components such as pipes, pumps, frictions, etc. under off-line conditions.

Dynamic calibrations aim tuning the dynamic characteristics of a process. It makes use of multisampling points to dynamically decide stable and accurate operations of the process under different conditions. It makes use of various mathematical tools such as averaging, weighed average, multi-fixed-range averaging, standard deviation range averaging, etc.

In many cases, the calibrated variable has multiple inputs and outputs. In these cases, an input is varied in increments in increasing and decreasing directions over a specified range. The observed output then becomes a function of that single input. This procedure may be repeated by varying other inputs, thus developing a family of relationships between the inputs and outputs. In these multivariable situations, the input/output relationship usually demonstrates statistical characteristics. From these characteristics, appropriate calibration curves can be obtained, and statistical techniques can be applied for analysis.

Calibration Personnel

The calibration is conducted by the use of appropriate devices representing the reference standards and trained personnel. Appropriate devices are kept as secondary standards and working standards by the national authorities as well as the companies themselves. Calibration process involves set rules, regulations, and processes. During the calibration, the calibrating personnel may make the following assumptions:

1. Handling procedures are consistent.
2. Test item and reference standard respond in the same manner in the test environment.
3. Random errors associated with the measurement are independent.
4. Multiple measurements form a distribution curve with the same standard deviation.
5. The test item and reference standards are stable during the measurement.
6. The bias of the test item and reference standard are the same.
7. Once the calibrations are carried out, ideally, the difference is zero or the difference can be explained by appropriate charts and statistical relationships.
8. Calibration is repeatable yielding the same results over a period of time.

Skilled calibration personnel are essential for the precision of the calibration. Calibration personnel may have appropriate clothing (static free clothing, gloves, face masks, etc.) for safety as well as to avoid the possibility of contamination. Although fully trained and experienced, it is possible for different operators to produce different results. To overcome this problem, measurements by different operators can be plotted and compared. Another solution may be to employ separate calibration curves by same operator. This may not be a problem in automated calibrations.

Calibration Laboratories

In organizations, calibrations are conducted on site or in laboratories or remote locations. Large organizations may have several laboratories (called calibration laboratories) dedicated to different instruments and processes. Laboratories are accredited by authorities in accordance with the guidelines such as the ISO Guide 58. Accreditation is a formal recognition that a particular laboratory is competent to conduct specific tests and/or calibrations.

During the calibration process, the readings of the test item are compared with the reference standards such as resistors, length standards, voltage standards, and so on.

A successful laboratory calibration procedure requires the following basic steps:

- Selection of an appropriate reference standard with known values covering the range of interest
- Conducting calibration curves (i.e., least-squares fit) to establish the relationship between the measured and known values of the reference standard
- Correction of measurements by using calibration curves
- Preparation of the appropriate documentation of the calibration procedure, results, analysis, and interpretation of results for the client

Once procedure adapted, the calibration relies on the instrument continuing to respond consistently and in the same way during the calibrations. If the system drifts or takes unpredictable deviations, the calibrated values may not be easily corrected for errors and bias, thus degrading the accuracy of the measurements.

Calibration Institutions

Many institutions provide comprehensive calibrations services. A typical institution can provide the followings:

- Force
- Pressure
- Weight and mass
- Metrological
- Dimensional
- Temperature
- Flow equipment
- Electronics test and measurement equipment

Customers of an institution can have a wide range of industries, such as automotive, aviation, contractor engineering, food and beverage, manufacturing, marine, metal and mining, nuclear, oil and gas, petrochemical and chemical, pharmaceutical, power and energy, pulp and paper industries, and so on.

Some institutions develop, manufacture, and market calibration equipment, software, systems, and services for the calibration and maintenance of process instruments. Their product range includes portable calibrators, workstations, calibration software, accessories, industry-specific solutions, and professional services. They will comply with customer requirements for accuracy, versatility, efficiency, ease of use, compatibility, and reliability.

Calibration Records

Calibration history is an important part of knowing data quality. The records can be kept in software environment or in printed formats. Many companies provide software in data file format that enables the sharing of structured data across different information systems. Data fields such as position ID, device ID, location, serial number, and work order number can be transferred from one form to another suitable for engineers to evaluate or the managers to view. In addition, the data can include maximum errors, pass/fail notifications, calibration date and time, calibration frequency, who carried out the calibration task?, and so on.

Once calibrations are completed, the calibration labels are often used for individual instruments as they supply information on efficiency and applicability of instruments. They indicate parameters of instrument, tolerances, and special conditions of use. Calibration labels need to conform to the requirements of ISO/IEC 17025 general requirements for the competence of testing and calibration laboratories. ISO 17025 requires the following:

- All measurement equipment should be securely and durably labeled.
- The labels should clearly indicate the name of the calibration laboratory, date of calibration, due date, usage equivalent, and the authorized officer.
- Information on label must be legible and durable under reasonable use and storage conditions.
- When it is impractical to affix a label directly on an item, the label may be affixed to the instrument container.
- Temper resistance seals may be used when necessary.
- Functional labels should contain reference standards.

CALIBRATION SOFTWARE SUPPORT

Calibrations are mostly conducted by using computers to capture and analyze data. Once the results are obtained, software packages assist in analyzing the information. Most packages use method of least squares for estimating the coefficients. Some of the packages are capable of performing weighted fit if the errors of the measurements are not constant over the calibration interval. The spreadsheets and software packages provide information such as coefficient of calibration curve, standard deviations, residual standard deviation of the fit, goodness of the fit, and so on.

Use of Spreadsheets

A set of spreadsheets are used to perform random-number driven simulations, including single standard, bracket, calibration curve, and standard addition methods. These simulations include additive and multiplicative interferences (systematic errors) and random errors in both signal and in measurements. It is possible to observe how non-linearity, interferences, and random errors combine and attempt to optimize precision and accuracy of the measurement.

Some of these spreadsheet models are

- Calibration curve method with linear fit
- Calibration curve method with non-linear fit
- Single standard addition method
- Multiple standard addition method

Calibration Management Software

A typical calibration management software (CMS) schedules calibrations, tracks usage and locations, maintains histories, generates work orders, calibration certificates, and calibrations labels, and supports web-based access. They support information on short- and long-term effects on the devices, linearities, and stability.

CMS may have automated features. Automated calibration management system promotes efficient management of plant assets and field instruments in one database. They generate future calibration schedules and alerts on the past failed calibrations. Most CMS complies with the ISO 17025 requirements. Some examples of the current common software are as follows:

1. *Ape Software*—(Calibration control) Intuitive database program that organizes calibration data for gages and other test equipment
2. *AssetSmart*—Web-based asset, calibration, material and tool maintenance management software
3. *BDR Systems*—Preventive calibration system that provides monitoring, tracking, and control of the calibration function
4. *Beamex*—CMS for documenting, planning, analyzing, and optimizing calibration work
5. *CompuCal Software*—Online compliant calibration and maintenance management that ensure quality compliance with 21 CFR Part 11, GxP, ISO, and PAT initiatives
6. *CyberMetrics*—GAGEtrak—CMS
7. *Diversified Data Systems*—(OpenMETRIC) Calibration and metrology data management and tracking software for ISO 17025 and ISO 9000 with 21 CFR Part 11
8. *GrandRavine Software*—(MaintScape) Includes facility maintenance software, plant maintenance software (CMMS and FMS) and CMS
9. *Honeywell International*—DocuMint automated calibration management system that promotes efficient management of plant assets and field instruments in one database
10. *IBM*—Maximo calibration. Provides all requirements for traceability and reverse traceability, all calibration history data, calibration data sheets, and reporting
11. *IndySoft*—Gage InSite. CMS package with an emphasis on security and flexibility

Integration of Calibration with CMMS

Many companies make efforts to integrate calibration software with the computerized maintenance management system (CMMS) due to the following benefits of integration:

- Plant hierarchy and all work orders for process instruments can be generated and maintained in the customer's CMMS.
- Calibration work orders can be transferred to a CMS.
- Companies save time, reduce costs, and increase productivity by preventing unnecessary double effort and rekeying of work orders in separate systems.
- Integration also enables companies to automate their calibration management process with "smart" calibrators.
- Seamless integration of IT systems across plants and remote sites.
- Sharing of critical plant and process information.
- Productivity improvement, cost reduction, and improving quality by eliminating manual errors in rekeying data.

COST OF CALIBRATION

The cost of calibration depends on what is calibrated and who is calibrating it. In simple cases, where a single instrument is involved the cost can be lower than one hundred dollars, but complex cases can cost thousands of dollars. Calibration cost depends on where the calibration is carried out and whether it takes place in specially setup laboratories or on the plant. The cost of calibration may be dependent on the availability of expert in-house personnel or outsourcing it to third parties. Certification by ISO 10012-1, ISO 9001, MIL-STD 45662A, requires careful calibration of the measuring equipment used in the process. Also, in some cases such as the weighting systems calibration is a statutory requirement.

One of the major factors for cost is the frequency of calibration. In most cases, a validity period is issued during which calibrated devices can be used without concern for major errors and uncertainties. Some organizations conduct calibrations at regular intervals, while others opt for conservative calibration intervals simply to meet the legal demands. Nevertheless, the use of uncalibrated instruments in an organization can be costly as it may affect the product quality and the quality of downstream operations.

Standards such as ISO 10012 suggest regular and well-organized calibration intervals. As a rule of thumb, 85%–95% of all instruments returned for calibration must meet the calibration limits determined by the probability chart of age and failure data. Usually, an instrument must be calibrated if failure rate increases or functionality deteriorates when compared to other standard devices. In this respect, a number of different mathematical techniques, such as the Weibull statistics and renewal equations, can be employed. A range of software (e.g., the visualSMITH and Calibration Manager) are available for determining the calibration intervals and the cost analysis.

MEASUREMENT ASSURANCE PLANNING

Measurement assurance planning (MAP) is a group of activities designed for critical evaluation of measurements. The MAP is first used by National Aeronautics and Space Administration (NASA) and National Institute of Standards and Technology (NIST) for calibration of Earth observing system satellites, ground-based and airborne instruments in space explorations. The ideas and procedures of MAP later have been adapted by many organizations as guidelines in measurement and calibration activities under different names such as Volt MAP, Mass MAP, Accelerometer MAP, etc.

NASA applies MAPs to achieve accurate, precise, and consistent long-term series of radiometric measurements from multiple instruments in multiple platforms. It is realized that the success of the process depends on proper calibration of all instruments against a set of recognized reference standards. Accurate performance of individual instruments leads to better accuracy and better performance at the collective system level.

LITERATURE ON CALIBRATION

Literature on calibration is available from various sources. These are as follows:

1. *Manufacturers* supply comprehensive information about calibration requirements of their products.
2. *Regulating authorities and standards institutions* supply information calibration requirements of instruments and devices. Calibration can be statutory particularly where health and safety is important.
3. *Calibration services* provide information on calibration processes.
4. *Organizations* provide rules and regulations for their equipments for assurance planning.
5. *Books* provide information calibration issues and processes.

Many nations and organizations maintain laboratories with the primary functions of calibrating instruments and field-measuring systems that are used in everyday operations. Examples of these laboratories are Standards Council of Canada, NIST, National Association of Testing Authorities of Australia and the British Calibration Services, and Australian Standards. Some important information on calibration can be found in sources of ISO, IEC, IEEE, and national standards publications. A few of these publications are briefly explained in the following.

ISO 17025 is an international standard for calibration and testing laboratories. It requires laboratories to demonstrate that they operate a quality system covering processes, documentation, and quality management. The laboratories need to generate technically valid results accounting of the equipment procedures and personnel. Information on ISO 17025 can be found in many books or ISO publications (http://www.fasor.com/iso25/).

The military standards MIL-STD-4566A is a standard that describes the requirements for creating and maintaining calibration systems for measurement and testing. Available at http://store.mil-standards.com/

TRENDS IN CALIBRATIONS

With the availability of advanced technology, the classical calibration process is changing at least in three fronts, these being

1. Electronic calibrations
2. Intelligent, soft calibration, and self-calibrations
3. Remote and e-calibrations

These techniques will be explained next and some examples will be given.

Electronic Calibration

Many modern instruments offer features for closed-case calibrations so that electronic calibration can be employed. Electronic calibration is a single connection and one- or two-port calibration technique without tempering the components inside the case. Once the calibrating equipment, for example, computer, is linked with the device under calibration, appropriate software generates the necessary calibration information. Errors due to gains and offsets of the instrument are corrected mathematically within the instrument processor to obtain the correct measured values. Analogue corrections can also be made via the adjustment of the parameters of some components such as the digital-to-analogue converters. Corrected calibration constants are kept within the non-volatile memory for permanent use.

As an example of this method, Agilent electronic calibration modules 8719, 8720, 8722 microwave network analyzers provide a broad frequency range of calibrations from 10 MHz to 67 GHz (http://we.home.agilent.com/). Similarly Fluke offers electronic calibration facilities for multifunction process, pressure, and temperature instruments (http://www.fluke.com/).

Self-Calibrations

With the wide applications of digital systems, many intelligent instruments are available and widely used in the process industry. Many of these intelligent instruments have self-calibrating features. In self-calibrations, post-measurement corrections are made, and the magnitudes of various errors are stored in the memory to be recalled and used in the laboratory and in the field applications.

Apart from the intelligent instruments, many intelligent (smart) sensors are being employed. These smart sensors have digital programmable calibration features as shown in Figure 7.1. Particularly sensors complying with IEEE 1451.4 standards provide comprehensive transducer electronic datasheets that contain configuration, scaling, and calibration information necessary to make measurement through mixed-mode interface. Many smart sensors are capable of calibrating themselves, scaling the incoming data, computing statistics, and communicating with other digital systems on the network. Most commercially available software permit calibration of smart sensors and upload the new parameters directly to the circuitry of the sensors.

In an application of smart sensors (e.g., the Atmos SSP14 Sensor Signal Processor family) (http://www.sensorsmag.com/), have memory that is programmed at the factory with a set of default zero and span curves defining the relationships with the physical phenomenon. These default curves represent average sensor output adjusted for the most accurate response at the room temperature. Each time calibration is done and the appropriate zero or span curve adjusted in the vicinity of the desired functionality points.

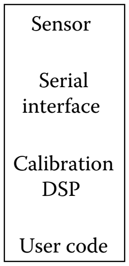

FIG. 7.1
Main features of self-calibrating smart sensors.

Soft calibrations is a strategy for constructing a global multivariate calibration model that includes calibration samples measured over time on different days is used in analysis.

Remote and e-Calibration

A new trend of calibration is the Internet calibration. Internet calibration technique is supported by web-accessible test procedures, and appropriate hardware and software.

As examples of Internet calibrations Fluke, the United Kingdom, offer calibration systems for the Fluke 4950 multifunctional instruments (http://www.npl.co.uk/). On the other hand, Anritsu is active in investigating the possibilities of Internet-based calibration by using portable optical time domain reflectometer (OTDR) MW9076, (http://www.electronicstalk.com/news/anr/anr163.html). The OTDR is controlled via the Internet with the aid of appropriate software. The software can be controlled through a PC via modem, mobile telephone access, or PCI cards. Internet calibration is supported by appropriate software that includes the mathematical models of the interface electronics and optimizes calibration on that basis of this model.

Because of growing importance e-calibrations will be explained in the next section.

INTERNET CALIBRATION

Regular calibration is essential for quality and traceability to national and international standards. One way of achieving traceability is to send the instruments to be calibrated and acquiring certificate and correction values from a National Measurement Institute (NMI). In many cases, the value of settings can be affected by transport leading to uncertainty. This exercise can be costly and time consuming. Also, in many cases in the process industry, some of the equipment is bulky for transport and dynamic calibrations are necessary on-site. A solution to these problems is the e-calibrations through the Internet. This reduces the transportation needs, environmental effects, downtime, cost issues, and the need for in-house expertise.

Internet assists calibrations to take place in a number of ways:

1. Internet acts as a means of exchanging information between two remote sides with human operators at each end using interactive links.
2. Remote monitoring of the sensors.

Internet calibration consists of the operations to be performed for maintaining the system tuned for properly executing the process tasks in hand. Measurements rely on the available standards and the associated software suitable for Internet calibrations. Typical requirements of Internet calibrations are

1. A computer connected to the Internet
2. Appropriate calibration software

3. A login name and password to use the service
4. Understanding of basic calibration principles
5. Understanding of the principles and functionality of the instrument under calibration
6. Understanding of scientific principles

Once a computer has been connected to the measurement system to be calibrated, the computer needs to log on to the calibration service provider. Services that offer online calibrations are known as *Internet Calibration Services* or iCals.

Once connected to the system, iCal instructs the operator, in the correct order, to perform the measurements. Effectively, it provides the operator with a soft procedure to perform the measurements. Once the measurement procedure is completed, the system generates the required final data with uncertainties ascertained from the measured and database information, providing the operator with a certificate if applicable.

During the measurement process, there is potential for the iCal system to provide measurement assistance screens with video or procedural details for specific parts of the process. In addition, it provides the administration with any measurement procedural changes through new international standards and ensures all groups are following common guidelines. The new data and historical records are automatically kept on the website and can be accessed and checked by the service users.

Internet Calibration Examples

One of the first iCal services was developed by the United Kingdom's National Physical Laboratory. It was combined the technology of remote monitoring, remote control, and NMI calibration techniques for application in a microwave frequency measurement system called *vector network analyzers* (VNA).

In this application, the client enters the required measurement parameters and is offered options based on the knowledge the NMI has about the client's equipment. From this point, the entire measurement process is controlled by NMI. VNAs provide a swept frequency measurement of the transmission and reflection coefficients for an electrical network. Calibration is performed using instrument firmware and a set of standard devices, all of which are assumed to be ideal and are available as standard items from the VNA manufacturer. The correction of the measurement data to that of the NMI comes via precision verification artifacts, air-spaced transmission lines, attenuators, and terminations, whose properties change little over time. Once the calibration is completed, all correction factors are stored in an online database.

There many other examples of Internet calibration and metrology in the process industry, medical, and optical networks markets. The optical communications network provides a method of a real standard transfer for wavelength measurements.

CALIBRATION EXAMPLES

A few examples of calibrations are given in the following.

Flow calibration: There are many devices available for the measurement of liquid, air, or solid flow. Once the method of measurement is determined by the use of appropriate flowmeter static or dynamic calibrations can be carried. For example, in the case of static-gravimetric liquid flow, a calibration facility may include a reservoir, a pumping system, piping system, flowmeter under test located on the pipeline, collection system, computers and interface, and supporting software. The calibration of flow of fluid through the meter can be determined by collecting prescribed mass of steady fluid flowing over a measured time interval.

The calibrations flowmeters fall into three distinct categories:

- Factory calibration
- Initial site calibration
- Routine site recalibrations

All size flowmeters, large or small, can be calibrated by mobile or static test rigs. Flowmeter calibration is very important in international trade of oil and other bulk fluid movements. Therefore, flowmeters require to be calibrated against accurate reference standards traceable to internationally accepted primary standards.

Sensor calibration: Sensors may have to be calibrated after having integrated with a signal conditioning system. This process requires an injection of known input signal into the sensor. By observing the output a correct output scale can be configured for that particular application. If the sensor is used for time varying inputs, the dynamic calibration becomes necessary. In most cases, transient behavior of sensor top step response may be sufficient to assess the dynamic response of the sensor.

Calibration of chemical mixtures: As food contains many chemical substances the calibration of devices becomes complex. For example, in the case of honey in food-processing industry the following parameters need to be identified by calibrating instruments: fructose, glucose, maltose, moisture level, acidity, etc.

Static pressure calibrations: For example, for aircraft pressure transducers, pressure up to 500 psi can be calibrated on computer-controlled automatic test facilities, using gas as the pressure medium. Ranges above 1000 psi can be calibrated manually using hydraulic media. Most calibration standards can have accuracies better than 0.01%.

In an application, the computer-controlled calibrations are performed at zero and 20% increments of full scale to 100%. Manual calibrations are performed at 0% and 25% increments of full scale. For all transducers, the test data is fed into a computer which calculates the test parameters, plots nonlinearity, thermal zero shift and thermal sensitivity shift, and prints out the test report. The computer then compares the test data with stored specification limits and accepts or rejects each transducer.

Measurements are first made at zero pressure, then two times full scale, then zero, to establish zero shift after 2× FSO. Then two complete cycles from zero to full scale and return are performed, measuring output at 20% (or 25%) increments. These data points are used for calculation of nonlinearity, hysteresis, and non-repeatability.

Dynamic pressure calibrations: In some cases, dynamic characteristics can be established from periodic static calibrations. However, in many cases, the accuracy available in dynamic measurements cannot be extrapolated from only static calibrations. Several of the more commonly used methods of dynamic calibration are as follows:

- Comparison pressure calibrations can be performed dynamically with a range of sinusoidal pressure generators.
- Hydraulic pressure generators can be used. They incorporates a compression spring, piston and seismic mass assembly, hydraulic oil filled chamber, and mounting cavities for the reference standard and test transducers. Sinusoidal vibratory motion applied to the generator housing imparts sinusoidal pressure to oil which is exposed simultaneously to the sensing surfaces of both transducers providing a direct comparison calibration capability.
- Sinusoidal vibration of a vertically mounted liquid column provides a dynamic pressure that can be applied to a test transducer mounted at the bottom of the tube. By attachment to an electrodynamic vibrator, short liquid columns can be used to provide about 5 psi from about 50–2000 Hz. Low frequency is generally limited by the vibrator and the high frequency is limited by the resonance frequency and damping of the liquid column.
- The inlet modulated pressure generator consists of a wheel with holes drilled through its periphery which is rotated at high speed. Air is blown through the holes from one side of the wheel and there is a cavity on the opposite side of the wheel in which are located the transducer under test and a reference transducer. The frequency of the signal generated is directly proportional to the speed of rotation. Frequencies of up to 12 kHz can be generated with pressure amplitudes of 1 bar at 1 kHz falling to 0 1 bar at 12 kHz. Static mean pressures can be generated.
- The Gulton whistle consists of a tube which is sharp edged at one end and is closed with a moveable piston at the other. Air which is blown over the edge of the tube excites the first organ pipe resonance. The resonant frequency is adjusted by the position of the piston within the tube. Mounted in the piston are the reference pressure transducer and the transducer under test.
- Small shock tubes are often used to provide rise time and frequency response characteristics for transducers. Because of difficulties in determining the pressure level in the step, shock tubes are not usually used for pressure sensitivity calibration. Pressure rise times of about 1 µs are practical, which permits transducer characterization to frequencies beyond 100,000 Hz.

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